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ORIGINAL ARTICLE

Impacts of forest types on soil C, N and DOC loss in runoff in the laterite hilly region of southern China

Sun Liying · Yang Fengting · Wang Jingyuan · Fang Haiyan · Qi Junyu

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Abstract Forest plantations significantly impact soil properties and hydrological processes. Field investigation was carried out to provide insight into the impacts of three forest types (*Cunninghamia lanceolata, Pinus elliottii*, and mixed forest of *Schima superba* and *Cyclobalanopsis jenseniana*) on soil organic carbon (SOC), total nitrogen (TN) and the removal of dissolved organic carbon (DOC) by runoff. SOC and TN contents were measured in soils (0–50 cm) under three forest types on both uphill and downhill. Runoff samples were collected and DOC concentrations were analyzed after 27 erosive rainfalls during the period of April 2011 to April 2012. Results showed that the lowest contents of SOC and TN in top soil layer (0–10 cm) were observed in pure *C. lanceolata* stands. Vertical distributions of SOC and TN in pure *C. lanceolata* and pure *P. elliottii* followed negative power functions on downhill ($P < 0.005$), while those in mixed *S. superba* and *C. jenseniana* followed negative exponential functions on downhill ($P < 0.005$). DOC concentrations showed no significant correlation with runoff, and the average values were following the order of mixed *S. superba and C. jenseniana* > *C. lanceolata* > *P. elliottii* in 27 erosion rainfall events. The runoff and DOC loss density (DOC_{ld}) showed significantly positive correlations with throughfall ($P < 0.001$) and their average values followed the same order as *C. lanceolata* > mixed *S. superba* and *C. jenseniana* > *P. elliottii*. The lowest SOC content and the highest DOC_{ld} value were observed in pure *C. lanceolata* stands, which should be well considered when the large-scale reforestation was conducted in the laterite hilly region of southern China.

Keywords Reforestation · Tree species · Throughfall · Soil organic carbon · Runoff

Introduction

Soils play a significant role in the continental and regional carbon (C) and nitrogen (N) balance, due to their great contribution to the global warming via the emission of greenhouse gases (CO_2 and N_2O) into the atmosphere (Wang et al. 2012; Zhang et al. 2013). As soils are the largest carbon pool in the terrestrial ecosystem, even a comparatively small change in soil C content may give rise to an important net exchange of C between soils and atmosphere (Zhang et al. 2013; Almagro and Martínez-Mena 2014). Total nitrogen (TN) in soil is often closely coupled with soil organic carbon (SOC), and both of them are influenced by natural and anthropogenic factors, such as precipitation, vegetation type, topography, soil properties, land use and management practices (Wang et al. 2012; Rezapour 2014). Extensive studies have been conducted in the past 20 years to understand the impact of natural and

S. Liying · F. Haiyan (✉)
Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
e-mail: fanghy@igsnrr.ac.cn

Y. Fengting · W. Jingyuan
Qianyanzhou Ecological Station, Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Q. Junyu
Faculty of Forestry and Environmental Management, University of New Brunswick, P.O. Box 44555, 28 Dineen Drive, Fredericton, NB E3B 6C2, Canada

human disturbances on SOC and TN contents for the evaluation of greenhouse gas emission (Song et al. 2013; Yang et al. 2005; Wang et al. 2012).

A number of studies have demonstrated that the SOC accumulation varies significantly from different tree species, and the conversion of forest type may result in great variations in the storage and distribution of SOC and TN (Zheng et al. 2005; Hansson et al. 2013; Gurmesa et al. 2013). Also, the vertical distribution of SOC in soil profile was significantly influenced by forest type (Yang et al. 2005; Wang et al. 2009). Many characteristics of forest species could have important impacts on SOC and TN: (i) shading, frost protection, throughfall and uptake/transpiration of soil water; (ii) litter production, including both leaf fall aboveground and roots belowground; (iii) production of root exudates, and interactions with root symbiotic organisms (Prescott and Grayston, 2013; Gurmesa et al. 2013). Among these, litter production and decomposition (both aboveground and belowground) have been recognized as the most important factors influencing SOC and TN (Song et al. 2013; Wang et al. 2013). The quality of litter fall may directly impact SOC and TN accumulation and further change the C and N cycling via its impacts on soil microbial community and soil acidity when decomposed (Guo et al. 2005; Aponte et al. 2013). However, the mechanisms of different plant effects are still not clear.

Besides, intensive investigations were focused on the soil C loss via transportation of dissolved organic carbon (DOC) from soil to runoff, due to the high mobility, reactivity of DOC and its significant role in surface water (Strohmeier et al. 2013; Yang et al. 2013; Gaelen et al. 2014). SOC loss in runoff involves complex processes caused by production, adsorption and desorption of DOC in soil, which are influenced by hydrological processes interacting with biogeochemistry of terrestrial and aquatic ecosystems (Kalbitz et al. 2000). Rainfall is considered to be one of the major driving forces for the transport of DOC from soil to runoff (Hua et al. 2014). Positive correlations between DOC loss discharge and rain events were observed in different catchments (Grieve 1994; Suhett et al. 2007). The effects of extreme storm events on C export in runoff from forested catchments are considerable (Dhillon and Inamda 2013). Also, DOC export was found to be related with the discharge of overland flow, basin slope, SOC amount and the area of soils (Ludwig et al. 1996; Strohmeier et al. 2013; Hua et al. 2014). Although studies on DOC in soils and catchments have been published in the last decade, the transition of DOC from soils to runoff is still poorly understood (Strohmeier et al. 2013).

As one of the China's bread baskets, the laterite hilly region of southern China covers about 1.18 million km^2. The soil of this region is mainly red loams with high *Fe* and *Al* content (Shi et al. 2009). Great efforts have been devoted to control the ever-increasing soil loss induced by the severe soil erosion in this region (Higgitt and Rowan 1996; Liang et al. 2010). As a result, large-scale plantations have been carried out in southern China since 1980s, contributing about 65 % of the C sink in the regional terrestrial ecosystems (Wang et al. 2009). During the reforestation process, large areas of pure *Cunninghamia lanceolata* stands were established for an anticipated high economic refund, leading to a sharp decline in the forest area of broadleaved trees (Guo et al. 2006). The shifts of forest types would impact soil C and N distribution and lead to great changes in uptake or emission of CO_2 from forests to the atmosphere in long term.

In this study, the SOC and TN contents were compared among three types of forestation, pure *C. lanceolata*, pure *Pinus elliottii* and mixed *Schima superba* and *Cyclobalanopsis jenseniana* in the laterite hilly region of southern China, where large-scale plantations were carried out during the last 20 years. In addition, the removal of DOC in runoff from soil C under three types of forests was also addressed.

Material and method

Study area

The study site, Qianyanzhou Research Station, is located in Taihe County (115°04′E, 26°44′N), Jiangxi Province, China (Fig. 1). The station occupies an area of 208 ha, covering three watersheds with iron-enriched laterite soils and typical subtropical monsoon climate. The mean annual temperature is about 18 °C and the mean annual precipitation is about 1,489 mm (mostly occurring in April to September).

The land-use changes (Fig. 2) and plant species areas' distribution (Table 1) from 1983 to 2002 in Qianyanzhou Research Station indicate that only 27 % of the land area was covered by woodland, including bushes and *Bamboos* in 1983. The Institute of Geographic Sciences and Natural Resources Research (Chinese Academy of Sciences) has conducted reforestation here since 1983. Woodland habitat had increased sharply since 1983 and remained nearly stable at 59 % of the landscape after 1990. After reforestation, *P. massoniana* (45.62 ha) and *P. elliottii* (40.38 ha) were dominant plant species, with other important species, like *C. lanceolata* (7.15 ha), mixed *C. lanceolata* and *S. superba* and *C. jenseniana* (10.39 ha.) and mixed *S. superba* and *C. jenseniana* (5.78 ha).

Soil sample collection and measurement

Soil samples were collected in April 2011 at the beginning of the rainy season. The sampling locations were selected

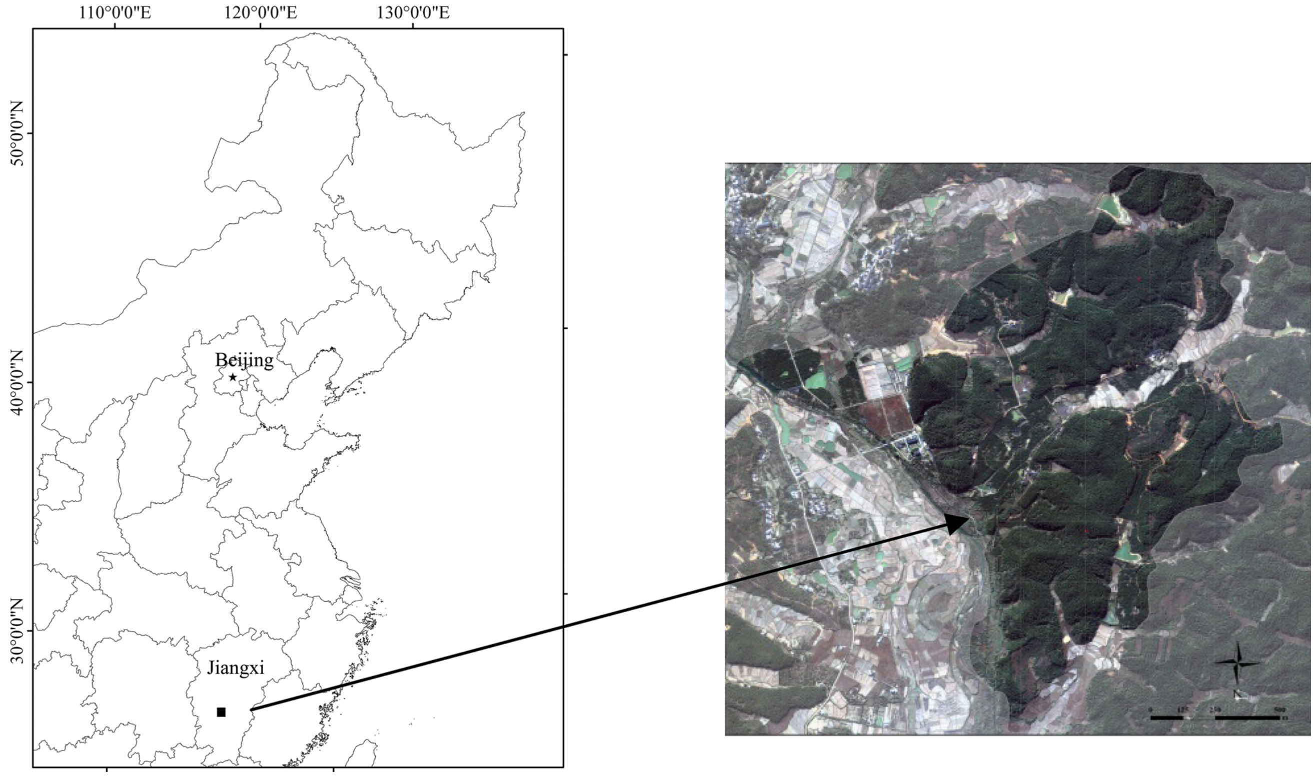

Fig. 1 Location map of study area (Qianyanzhou Research Station) in China

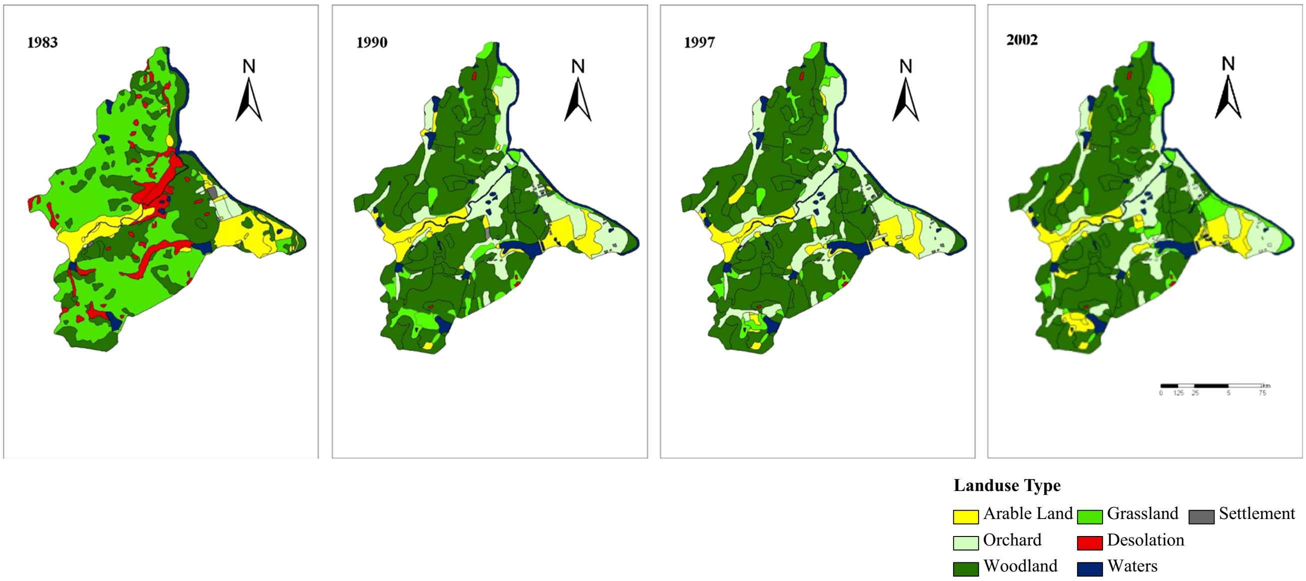

Fig. 2 Land-use changes of Qianyanzhou Research Station for the years 1983, 1990, 1997 and 2002

outside but adjacent to plots in three forest types to avoid disturbance to runoff samples collected from the plots. Soil samples were collected at 50 cm depth with 10 cm intervals for both uphill and downhill in three forest types. Litter horizons were removed before soil sampling. Three to five sets of samples were collected and mixed for each depth. All soil samples were kept in a cold container instantly in the field, and then transported to the laboratory and stored in the refrigerator at 4 °C before air drying and chemical analysis. Soil samples were air dried and passed through a 1-mm sieve to remove coarse materials such as gravel and roots. Then, the soil texture composition of the

Table 1 Areas of different plant species for the years of 1983, 1990, 1997 and 2002

Area (ha)	Year			
Plant species	1983	1990	1997	2002
Pinus massoniana	1.37	49.45	45.66	45.62
Cunninghamia lanceolata	–	6.88	7.15	7.15
Pinus elliottii	–	39.87	40.74	40.38
Schima superba and *Cyclobalanopsis jenseniana*	–	5.98	5.84	5.78
Bush	4.86	0.43	0.43	0.43
Pinus massoniana and *Pinus elliottii*	–	–		0.28
Oiltea Camellia	–	1.63	1.63	1.63
Tung Tree	–	0.95	0.85	0.51
Camphor Tree	–	–	2.78	2.78
Cunninghamia lanceolata and *Schima superba* and *Cyclobalanopsis jenseniana*	–	11.56	11.40	10.39
Bamboo	8.61	4.93	3.50	2.16

fractions <1 mm was analyzed. The SOC and TN contents were analyzed using elemental analyzer (Vario Max CN, Elementar, Germany).

Runoff sample collection and measurement

Three runoff plots were monitored in *C. lanceolata*, *P. elliottii* and mixed forest of *S. superba* and *C. jenseniana*, with the areas of 77, 113 and 73 m^2, respectively. Cement plot borders were constructed and metal barrels were used to collect surface runoff. Automatic rain gauges (RG13H, Vaisala, Finland) were used to record the rainfall amount from April 2011 to April 2012. The runoff amount was recorded by the water meters in the metal barrels. The throughfall amount was measured by rain gauges laid under trees, with one rainfall gauge monitoring an area of about 1 m^2.

There were 27 erosive rainfall events during the period of April 2011 to April 2012. Runoff samples were collected from the metal barrels at the end of three runoff plots. The collected runoff samples were firstly filtered through a 0.45 μm filter membrane, and then the concentration of DOC was analyzed with TOC analyzer (liqui TOC, Elementar, Germany). Problems were encountered during the studied period: (1) some throughfall records were found to be greater than the precipitation amounts; (2) some runoff amounts were not recorded due to the mechanical breakdown of the water meter on the metal barrels. As a result, complete dataset of runoff amount and throughfall was recorded for 17 rainfall events out of the total 27 rainfall events (Table 2).

Data analysis

To better understand how SOC and TN contents changed with soil depth, a rate of decrease (RD, %) relative to top soil layer (0–10 cm) was calculated using the Formula (1).

$$\mathrm{RD} = \frac{(\mathrm{SNC}_n - \mathrm{SNC}_1) \cdot 100}{\mathrm{SNC}_1}, \tag{1}$$

in which, SNC_n is the value of soil nutrient concentration (SOC or TN) of the *n*th layer, SNC_1 is the value of soil nutrient concentration (SOC or TN) of the first layer (0–10 cm).

The changes of SOC and TN contents with soil depth in three forest types were estimated by curve estimation tool with ANOVA analysis based on site mean values. Relationships between runoff, precipitation and throughfall were analyzed by linear regressions based on the site mean values. The DOC loss density ($\mathrm{DOC}_{\mathrm{ld}}$) was calculated using the Formula (2).

$$\mathrm{DOC}_{\mathrm{ld}} = \frac{\mathrm{DOC}_C \cdot R \cdot 1000}{A}, \tag{2}$$

where $\mathrm{DOC}_{\mathrm{ld}}$ is the loss density of DOC (mg/m^2), DOC_C is the concentration of DOC in runoff (mg/L), R is the runoff amount (m^3), and A is the area of the monitored plots (m^2). The relationship between $\mathrm{DOC}_{\mathrm{ld}}$ and throughfall amount was analyzed by linear regression with ANOVA analysis. All statistical analyses were conducted using SPSS 20.0 and the significance levels were set at $P < 0.05$.

Results

SOC and TN in the top soil layer (0–10 cm) on uphill and downhill

SOC and TN contents in the top soil layer (0–10 cm) under three forest types ranged from 6.15 to 19.53 g/kg and 0.77 to 1.52 g/kg, respectively (Table 3). On uphill and downhill, both SOC content and TN content in the top soil layer (0-10 cm) varied greatly under three forest types. The lowest content of SOC was observed in pure *C. lanceolata*,

Table 2 Measurement situations of 27 rainfall events

Date[a]	Precipitation (mm)	Duration (h)	Average rainfall intensity (mm/h)	Maximum rainfall intensity (mm/h)	Throughfall record (Y/N/U/G)	Runoff record (Y/N)	DOC (Y/N)
12/05/2011	66.0	12	5.5	12.6	Y/U	Y	Y
15/05/2011	15.4	4	3.9	1.4	Y/G	Y	Y
15/06/2011	21.9	5	4.4	13.4	Y/U	Y	Y
25/06/2011	16.0	6	2.7	5.0	Y/U	Y	Y
10/07/2011	23.8	1	23.8	23.8	Y/G	Y	Y
11/07/2011	5.8	2	2.9	5.6	Y/U	Y	Y
12/07/2011	51.0	4	12.8	2.0	Y/G	Y	Y
13/07/2011	47.0	11	4.3	26.2	Y/U	Y	Y
14/07/2011	25.8	6	4.3	12.2	Y/U	Y	Y
15/07/2011	5.6	3	1.9	4.8	Y/G	Y	Y
01/08/2011	10.4	2	5.2	6.8	Y/U	Y	Y
04/08/2011	9.2	1	9.2	9.2	Y/U	Y	Y
08/08/2011	21.6	4	5.4	11.6	Y/U	Y	Y
09/08/2011	17.6	8	2.2	9.2	Y/U	Y	Y
10/08/2011	6.0	4	1.5	3.2	Y/U	Y	Y
23/08/2011	25.4	7	3.6	12.2	Y/U	Y	Y
31/08/2011	27.8	14	2.0	4.0	Y/U	Y	Y
08/09/2011	22.4	2	11.2	14.0	Y/U	Y	Y
10/09/2011	18.4	4	4.6	12.2	N	N	Y
01/10/2011	34.6	17	2.0	5.8	Y/U	Y	Y
04/10/2011	12.8	9	1.4	1.4	Y/U	Y	Y
13/10/2011	69.3	9	7.7	30.8	Y/U	Y	Y
27/10/2011	6.3	8	0.8	0.8	N	N	Y
08/12/2011	8.8	12	0.7	1.0	Y/G	Y	Y
16/01/2012	2.2	6	0.4	0.6	N	N	Y
05/03/2012	46.8	15	3.1	11.0	N	N	Y
20/03/2012	1.2	6	0.2	0.2	N	N	Y

Y means there is a record for throughfall, *N* means no record for throughfall, *U* means the throughfall amount is under the precipitation amount, *G* means the throughfall amount is greater than the precipitation amount, *Y* means there is a record for runoff amount and DOC concentration, *N* means no record for runoff amount and DOC concentration

[a] Date is the expressed as dd/mm/yy

which were 35.0–56.6 % less than mixed *S. superba and C. jenseniana* and 50.9 % less than pure *P. elliottii* (Table 3). TN contents showed similar trend as SOC, the values of which in pure *C. lanceolata* were 11.5–44.1 % less than mixed *S. superba* and *C. jenseniana* and 31.9–39.9 % less than pure *P. elliottii*. The lowest of C:N ratios were (9.3 on uphill and 11.6 on downhill) also observed in pure *C. lanceolata*. No significant difference in C:N ratios were observed in pure *P. elliottii* and mixed *S. superba* and *C. jenseniana* (12.7–12.9 on uphill and 14.4–15.0 on downhill).

Similar results were observed in previous investigations. Wang et al. (2009) found lower SOC contents in pure *C. lanceolata* in top soil layer (0–10 cm) than mixed broadleaved forests at Huitong Experimental Station of Forest Ecology (26°40′–27°90′N, 109°26′–110°08′E), which is environmentally similar to Qianyanzhou Research Station. Jiang et al. (2010) observed higher SOC contents in pure *Liquidambar formosana* than pure *Pinus massoniana* at the reforestation demonstration area near Qianyanzhou Research Station in Taihe County. Wang and Wang (2007) also found much lower SOC contents in pure *C. lanceolata* stands than soils from native broadleaved forests at San Menjiang Forest (24°19′N, 109°36′E) in subtropical regions of southern China.

In addition, SOC and TN contents in the top soil layer (0–10 cm) were much higher on downhill than on uphill in all forest types. The SOC and TN contents in the top soil layer (0–10 cm) for different locations of slope and forest types were following the order of downhill in mixed *S. superba and C. jenseniana* > downhill in *P. elliottii* > uphill in *P. elliottii* > uphill in mixed *S. superba and*

Table 3 SOC, TN contents and the rate of decrease (RD) in different soil layers

Locations	Soil depth (cm)	*Schima superba and Cyclobalanopsis jenseniana*			*Cunninghamia lanceolata*			*Pinus elliottii*		
		SOC (g/kg)/ RD (%)	TN (g/kg)/ RD (%)	C:N	SOC (g/kg)/ RD (%)	TN (g/kg)/ RD (%)	C:N	SOC (g/kg)/ RD (%)	TN (g/kg)/ RD (%)	C:N
Uphill	0–10	9.46/0	0.87/0	12.7	6.15/0	0.77/0	9.3	12.52/0	1.13/0	12.9
	10–20	6.02/−37	0.61/−30	11.5	5.08/−17	0.60/−22	9.9	7.72/−38	0.77/−31	11.7
	20–30	6.51/−31	0.73/−16	10.4	3.49/−43	0.54/−30	7.5	5.14/−59	0.63/−44	9.5
	30–40	4.96/−48	0.67/−23	8.6	3.72/−39	0.46/−40	9.4	4.74/−62	0.58/−49	9.5
	40–50	6.51/−31	0.72/−17	10.5	3.70/−40	0.56/−28	7.7	4.71/−62	0.53/−53	10.4
Downhill	0–10	19.53/0	1.52/0	15.0	8.48/0	0.85/0	11.6	17.30/0	1.40/0	14.4
	10–20	14.21/−27	1.20/−21	13.8	6.03/−29	0.63/−26	11.2	8.20/−53	0.81/−42	11.8
	20–30	7.86/−60	0.80/−48	11.5	5.29/−38	0.60/−29	10.3	3.47/−80	0.44/−68	9.2
	30–40	4.56/−77	0.55/−63	9.7	4.57/−46	0.51/−40	10.5	2.44/−86	0.35/−75	8.1
	40–50	3.39/−83	0.53/−65	7.5	3.86/−54	0.50/−41	9.0	2.36/−86	0.35/−75	7.9
Relationship of SOC and TN	0–10	TN = 0.059SOC + 0.364; $F = 2{,}342.106$; $P = 0.000$; $R^2 = 0.988$								

C. jenseniana > downhill in *C. lanceolata* > uphill in *C. lanceolata* (Table 3).

Vertical distribution of SOC and TN in soils

SOC contents, TN contents and C:N molar ratios were highest in the top soil layer and decreased with soil depth in all three forest types (Table 3), which was consistent with previous investigations (Yang et al. 2005; Wang et al. 2009). The *RD* values suggested the depletion of SOC and TN with soil depths. It was found that *RD* increased with soil depths and the maximum of which were observed in soil layer (40–50 cm) reaching 86 and 75 % for SOC and TN, respectively.

Negative power functions can be used to describe the decrease of SOC contents and TN contents with soil depth in conifer forests on uphill (pure *P. elliottii*, $P < 0.005$) and on downhill (pure *C. lanceolata*, $P < 0.005$; pure *P. elliottii*, $P < 0.005$; Table 4). Although no significant power decrease of SOC and TN were found in pure *P. elliottii* on uphill ($P > 0.05$; $R^2 > 0.8$), similar trends were also observed. Negative exponential functions were fit to describe the vertical distribution of SOC contents and TN contents in mixed *S. superba and C. jenseniana* forest on downhill ($P < 0.005$). However, no significant exponential decreases were observed on uphill. Jobbágy and Jackson (2000) indicated that vegetation had slightly stronger impacts on the distribution of soil organic carbon with depth than climate, and the log–log function or log-linear function was well fitted for the estimation of soil organic C density in the first meter of soil. Power decrease of SOC with soil depth was also observed in conifer plantations by Wang et al. (2013).

DOC concentrations in runoff during the monitored rainfall events

The precipitation ranged from 1.2 to 69.3 mm for the 27 rainfall events during the period of April 2011 to April 2012 (Fig. 3a). DOC concentrations ranged from 4.09 to 20.38 mg/L in pure *C. lanceolata*, 3.29 to 45.98 mg/L in mixed *S. superba* and *C. jenseniana*, and 3.08–19.38 mg/L in pure *P. elliottii* (Fig. 3b). The average DOC concentration in three forest types followed the order of mixed *S. superba* and *C. jenseniana* > *C. lanceolata* > *P. elliottii*.

The monitored throughfall ranged from 1.7 to 68.0 mm in *C. lanceolata*, 2.0–57.4 mm in mixed *S. superba* and *C. jenseniana*, and 2.9–64.3 mm in *P. elliottii* (Fig. 3c). The average throughfall in three forest type followed the order of *C. lanceolata* > *P. elliottii* > mixed *S. superba* and *C. jenseniana* (Fig. 3c). Being consistent with the previous investigation (Tobón-Marin and Bouten 2000; Amori et al. 2012), significant positive correlations between throughfall and precipitation were observed in three forest types in the present study ($P < 0.001$, $R^2 > 0.6$; Fig. 4). Although no significant difference in throughfall was observed in three forest types, the relatively lower throughfall in mixed *S. superba and C. jenseniana* may be resulted from the slightly lower increase rate of throughfall with precipitation in mixed forest ($y = 0.700\ x - 2.659$, $P < 0.001$; $R^2 = 0.676$) than in pure *C. lanceolata* ($y = 0.887x - 4.591$, $P < 0.001$; $R^2 = 0.696$) and pure *P. elliottii* ($y = 0.749x - 1.647$; $P < 0.001$; $R^2 = 0.697$).

The runoff ranged from 0.004 to 0.385 m^3 in *C. lanceolata*, 0.001–0.281 m^3 in mixed *S. superba* and *C. jenseniana*, and 0.017–0.198 m^3 in *P. elliottii*. The average runoff followed the order of *C. lanceolata* > mixed *S.*

Table 4 Vertical distribution model of SOC and TN in three forest types

Location on hill	*Schima superba* and *Cyclobalanopsis jenseniana*		*Cunninghamia lanceolata*		*Pinus elliottii*	
	SOC	TN	SOC	TN	SOC	TN
Uphill	*$y = 8.675e^{-0.009x}$	$y = 0.779e^{-0.003x}$	$y = 13.813x^{-0.357}$	$y = 1.328x^{-0.255}$	$y = 53.788x^{-0.651}$	$y = 3.250x^{-0.471}$
	$F = 2.028$; $P = 0.250$	$F = 0.403$; $P = 0.571$	$F = 16.515$; $P = 0.027$	$F = 8.777$; $P = 0.059$	$F = 62.519$; $P = 0.004$	$F = 257.664$; $P = 0.001$
	$R^2 = 0.403$ ($n = 5$)	$R^2 = 0.118$ ($n = 5$)	$R^2 = 0.846$ ($n = 5$)	$R^2 = 0.745$ ($n = 5$)	$R^2 = 0.954$ ($n = 5$)	$R^2 = 0.988$ ($n = 5$)
Downhill	$y = 32.357e^{-0.046x}$	$y = 2.004e^{-0.029x}$	$y = 24.952x^{-0.467}$	$y = 1.785x^{-0.331}$	$y = 389.494x^{-1.342}$	$y = 12.209x^{-0.939}$
	$F = 230.065$; $P = 0.001$	$F = 64.103$; $P = 0.004$	$F = 261.885$; $P = 0.001$	$F = 93.851$; $P = 0.002$	$F = 101.365$; $P = 0.002$	$F = 86.692$; $P = 0.003$
	$R^2 = 0.987$ ($n = 5$)	$R^2 = 0.955$ ($n = 5$)	$R^2 = 0.989$ ($n = 5$)	$R^2 = 0.969$ ($n = 5$)	$R^2 = 0.971$ ($n = 5$)	$R^2 = 0.967$ ($n = 5$)

* y is the value of soil properties, x is the soil depth (cm)

superba and *C. jenseniana* > *P. elliottii* (Fig. 3d). Significant linear correlations between runoff and throughfall were observed in three forest types ($P < 0.001$; $R^2 > 0.5$; Fig. 5). The increase rate of runoff with throughfall followed the order of *C. lanceolata* ($y = 0.005x + 0.025$; $R^2 = 0.825$) > mixed *S. superba* and *C. jenseniana* ($y = 0.004x + 0.021$; $R^2 = 0.709$) > *P. elliottii* ($y = 0.003x + 0.024$; $R^2 = 0.584$), which showed the similar trend with the average runoff. Similar correlations of runoff discharge and throughfall amount were reported by Vega et al. (2005).

DOC loss density in runoff

DOC$_{\mathrm{ld}}$ ranged from 0.246 to 92.029 mg/m^2 in *C. lanceolata*, 0.025–42.600 mg/m^2 in mixed *S. superba* and *C. jenseniana*, and 0.049–21.809 mg/m^2 in *P. elliottii* (Fig. 6a). Also, DOC$_{\mathrm{ld}}$ showed significantly positive correlation with the throughfall in three forest types (Fig. 6b, $P < 0.001$; $R^2 > 0.6$). The average DOC$_{\mathrm{ld}}$ followed the order of *C. lanceolata* > mixed *S. superba and C. jenseniana* > *P. elliottii*.

Discussion

Tree species did affect SOC and TN and their vertical distribution in the laterite hilly region of southern China. Compared with mixed *S. superba and C. jenseniana* and pure *P. elliottii*, lowest SOC and TN in the top soil layer (0–10 cm) were observed in pure *C. lanceolata* in the present study. TN content (0–10 cm) was significantly positively correlated with SOC content (0–10 cm) in three forest types (TN = 0.059SOC + 0.364, $P < 0.001$; $R^2 = 988$; Table 3). Researches had been showing that SOC and TN were dramatically influenced by litter production, root exudates and the related bioprocesses (Wang et al. 2008, 2009; Guo et al. 2006). The SOC and TN were mainly determined by the quantity and quality of organic carbon in the plant (Shen et al. 2013). According to Wang et al. (2007, 2008), the higher production and decomposition rate of leaf litter in mixed plantations had resulted in higher surface SOC than in pure *C. lanceolata* plantation. They also indicated that the TN content was positively correlated with the mass loss of leaf litter. Berg (2000) indicated that higher contents of uneasy-decomposed components in conifer litter led to less C incorporation into the mineral soil than that in broadleaved forest. Fine root turnover was another important influencing factor on the flux of SOC (Wang et al. 2009). Jandl et al. (2007) indicated that the broadleaved trees may transfer more root detritus to the soil by the allocation of more biomass to their roots. Wang et al. (2009) observed more roots of

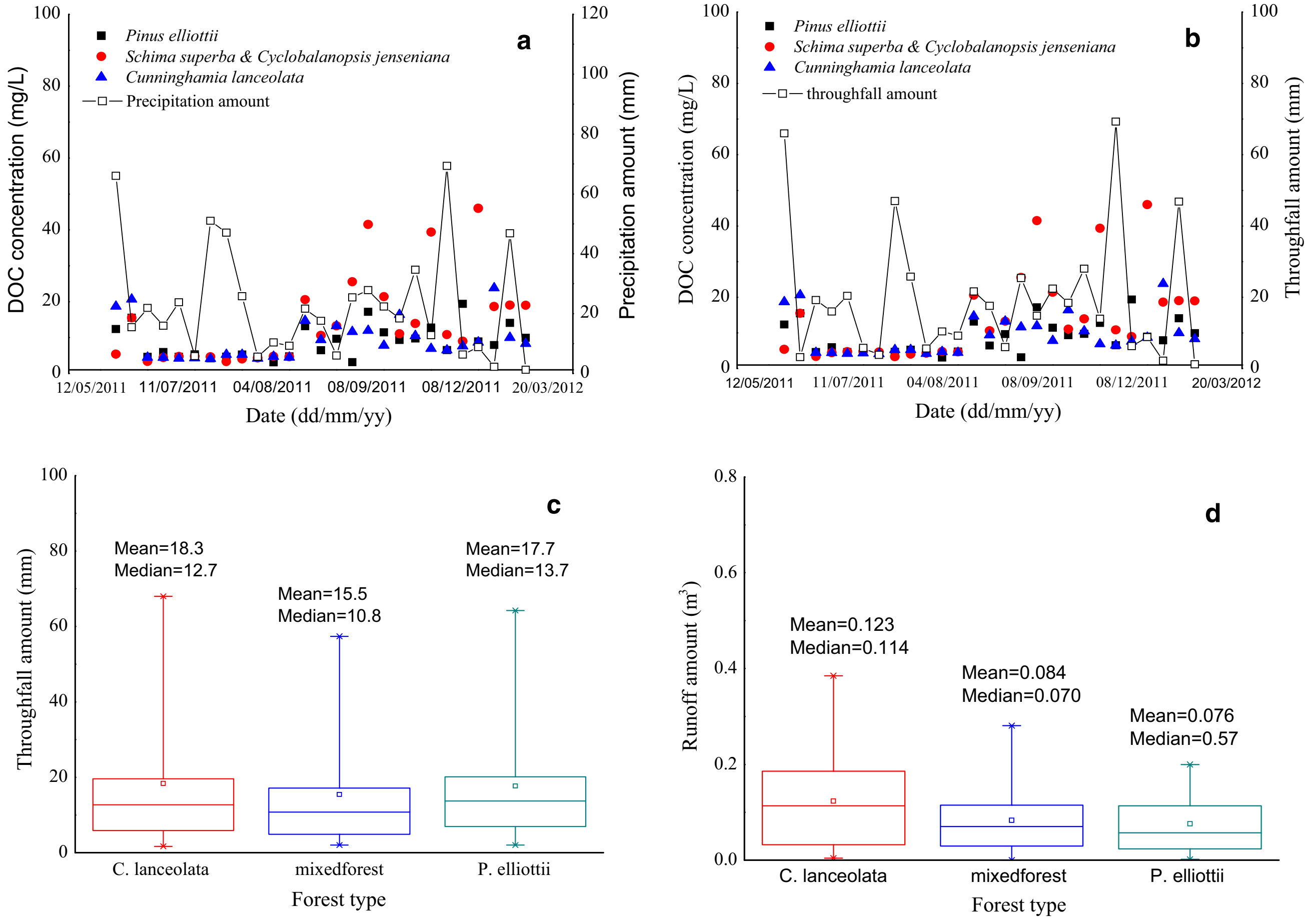

Fig. 3 Precipitation and DOC concentrations in 27 erosion rainfall events (**a**); range of throughfall (**b**), runoff (**c**) and DOC concentration (**d**) in three forest types

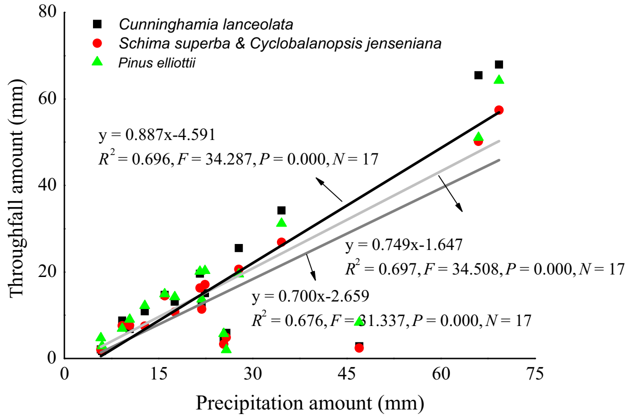

Fig. 4 Relationship between throughfall and precipitation for different forest types

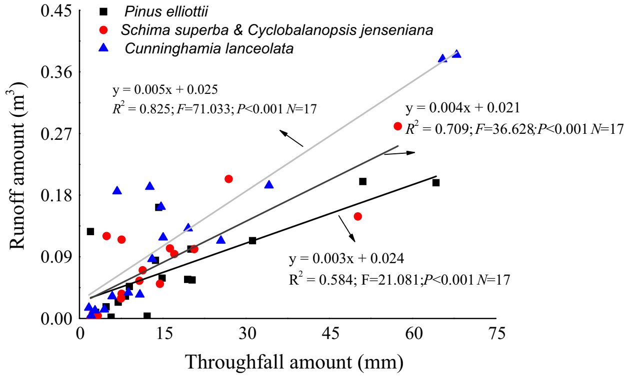

Fig. 5 Relationship between runoff and throughfall for the three forest types

broadleaved forest than pure *C. lanceolata* plantation. Also, soil fauna is of great significance to the incorporation of organic material from the forest floor into mineral soil (Fox et al. 2006). The higher degree of the richness and abundance of soil macrofauna were reported to result in the higher SOC in mixed forest of *C. lanceolata* and A. *cremastogyne* than the pure *C. lanceolata* stand (Yang et al. 2005). Theoretically, the relatively lower production and decomposition rate of leaf litter, lower roots' density and

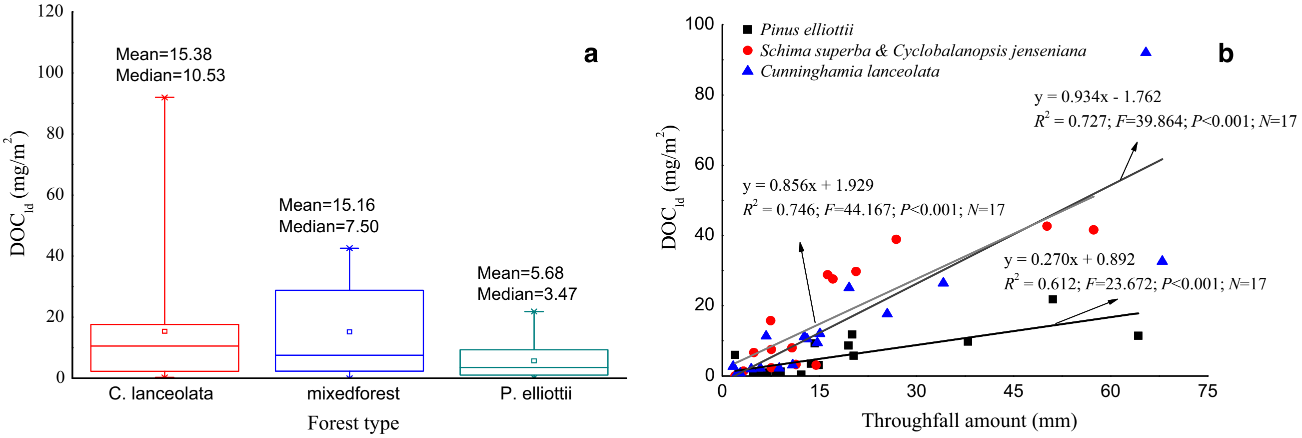

Fig. 6 Range of DOC$_{ld}$ and its relationship with throughfall

lower soil fauna may result in the lowest SOC and TN of the surface soil layer (0–10 cm) in the *C. lanceolata*.

Wang et al. (2009) indicated that SOC content decreased with depth and reached relatively low concentrations below 40 cm, with about 60 % of the SOC stored in the top 40 cm of soil layers (0–100 cm). In addition, Wang et al. (2013) observed higher SOC and TN concentration in surface soils (0–40 cm) than in deep soils (40–80 cm) due to the growth of coniferous roots within 40 cm soil depth. In the present study, no stable SOC content was observed in mixed *S. superba and C. jenseniana*. The stable SOC content was about 3.72 g/kg in pure *C. lanceolata* on uphill, about 4.74 g/kg in pure *P. elliottii* on uphill and 2.44 g/kg on downhill. The stable TN content was approximately 0.55 g/kg in mixed *S. superba and C. jenseniana*, 0.51 g/kg in pure *C. lanceolata*, and approximately 0.35 g/kg in pure *P. elliottii* on downhill. Most stable SOC and TN contents were observed in the soil layer of 30–40 cm. Although, vertical distribution of SOC and TN contents was followed the negative power distribution in both pure *C. lanceolata* and pure *P. elliottii*, the higher statistical power coefficients resulted in the fast decrease of SOC and TN content with soil depths in pure *P. elliottii*. As indicated by Jobbágy and Jackson (2000), vertical distribution was mainly determined by the plant allocation aboveground, belowground and between shallow and deep roots.

Redistribution of SOC and TN in different locations of slope should not be ignored. On uphill, the SOC and TN content in the top soil layer (0-10 cm) followed the order of pure *P. elliottii* > mixed *S. superba* & *C. jenseniana* > pure *C. lanceolata*. On downhill, the SOC and TN content in the top soil layer (0-10 cm) followed the order of mixed *S. superba* & *C. jenseniana* > pure *P. elliottii* > pure *C. lanceolata*. The SOC content ratio in top soil layer (0-10 cm) on downhill to uphill is about 2.1 times of that in broadleaved *S. superba* & *C. jenseniana* forest and about 1.4 times in both pure *C. lanceolata* and pure *P. elliottii*. Similar trends were also observed for TN content, with 1.8 times of TN on downhill to uphill in mixed *S. superba* & *C. jenseniana* forest and 1.1–1.2 times in conifer forest. This result suggested higher degree of SOC and TN storage in lower slope in broadleaved *S. superba* & *C. jenseniana* forest. Zhang et al. (2012) also indicated that the topography may have significant influences on soil erosion and soil properties in red soil region of southern China. They observed similar spatial trend of SOC and TN contents in the surface soil (0–20 cm), following the order of lower slope > upper slope > middle slope. And soil deposition may stimulate the C and N storage on the lower slope with slightly more strong accumulation of N than C. On the contrary, the relatively higher ratio of SOC on downhill to uphill may suggest slightly more strong storage of SOC than N with soil deposition in the present study. Higher statistical coefficient values in vertical distribution model of SOC and TN contents with soil depth suggested faster decrease of SOC and TN on downhill (Table 4).

Two reasons may cause the decrease of soil nutrients on uphill and the accumulation in the storage of organic C and TN on downhill. One is the tillage, such as long-term cultivation and intensive donkey-drawn tillage (Schumacher et al. 1997; Li et al. 2004, 2006). The other reason may be the redistribution of soil organic C in runoff caused by erosive rainfall (Jin et al. 2008; Zhang et al. 2006). For example, Zhang et al. (2006) demonstrated lower SOC content in erosion areas on upper and middle slope and higher SOC content in deposition areas on the lower slope. They indicated that water erosion played a significant role in SOC storage in depositional areas. In this study, the impacts of tillage on the redistribution of SOC and TN would be less significant, because there were no tillage actions since reforestation at Qianyanzhou Research Station in 1980s. Thus, erosive runoff may impose much significant impact on the observed SOC and TN patterns in the redistribution of soil nutrients. The higher ratio of SOC and TN content on downhill to uphill (Table 1) in broadleaved forest suggested the more significant impacts of runoff on broadleaved forests than conifer plantations in the laterite hilly region of southern China.

Recent studies have indicated the remarkable effects of interception by the canopies and stems among different trees on runoff and the concentrations of DOC (Currie et al. 1996; Guo et al. 2005). Also, the loss of DOC in runoff may be influenced by many factors, such as throughfall, soil organic C content and soil texture (Dalva and Moore 1991; Liu and Sheu 2003; Zhang et al. 2011; Möller et al. 2005). Throughfall occupied more than 90 % of the net precipitation and became the dominant water input below the tree canopy (Cao et al. 2008). Cao et al. (2008) observed the lower throughfall in conifer forest (*Pinus massoniana*) than in broadleaved forest (*Eucommia ulmoides*) in the laterite hilly region of southern China. However, in the present study, contrary results were observed with slightly higher averaged throughfall in conifer species (*C. lanceolata, P. elliottii*) than in broadleaved forest (mixed *Schima superba & Cyclobalanopsis jenseniana*; Fig. 3c). The differences in throughfall in three forests were increased with the increase of rainfall amount, especially when the rainfall amount is larger than 30 mm (Fig. 4).

It was reported that the solute transfer of organic carbon from the soil surface to overland flow is coupled with complicated processes, including transferring of solutes from soil surface by diffusion, raindrops' ejection on solution, erosion induced by raindrops and surface flow and adsorbing chemicals (Shi et al. 2011). As discussed by Hua et al. (2014), the DOC concentration could be either increased or decreased by the increase of runoff discharge. They indicated that overland discharge is a potential key regulating factor of DOC concentration in surface runoff and observed significant exponential relationship between DOC concentration and discharge in overland flow events. However, no significant correlations were found between DOC concentration and runoff in Qianyanzhou research station by the present study. Runoff did not have significant impacts on DOC concentrations. Fröberg et al. (2005) indicated that the addition of litter to the forest floor led to higher DOC concentrations. To some extent, higher DOC concentration in mixed *S. superba* and *C. jenseniana* was mainly resulted from the higher litter production in broadleaved forests as reported (Wang and Wang 2007; Wang et al. 2009). The amounts of SOC and leaf litter, and the partition coefficients of SOC and leaf litter between water and soil determined the DOC concentration in runoff under three forest types.

DOC loss is an interactive process between soil DOC and runoff water movement (Martin 2003). Dhillon and Inamda (2013) observed linear correlation of DOC flux with event precipitation from September 2010 to December 2011. In the present study, the $\mathrm{DOC_{ld}}$ was directly correlated with throughfall and indirectly correlated with precipitation (Fig. 6b). The increase rate of $\mathrm{DOC_{ld}}$ with throughfall followed the order of *C. lanceolata* ($y = 0.934x - 1.762$; $R^2 = 0.727$) > *S. superba* and *C. jenseniana* ($y = 0.856x + 1.929$; $R^2 = 0.746$) > *P. ellotti* ($y = 0.270x + 0.892$; $R^2 = 0.612$). To some extent, pure *C. lanceolata* can lead to higher DOC loss in runoff and deteriorate soil productivity by reducing SOC and TN content in top soil layer (0–10 cm). Compared with pure *C. lanceolata*, relative higher SOC and TN content and relative lower $\mathrm{DOC_{ld}}$ were observed in pure *P. elliottii*. Based on the above discussion, the alteration of pure *C. lanceolata* was necessary and the broadleaved forest or *P. elliottii* was recommended to be mixed with *C. lanceolata* in the reforestation in the laterite hilly region of southern China.

Summary

This research confirmed the influences of tree species on SOC and TN contents and their vertical distribution in mineral soil. Compared with mixed *S. superba and C. jenseniana* and pure *P. elliottii* stands, the pure *C. lanceolata* stands have resulted in 11.5 $\sim$ 50.9 % lower SOC and TN contents in the top soil layer (0–10 cm), which is assumed to be mainly influenced by the production and decomposition of litter in different species and should be further investigated. The dissolved organic carbon loss ($\mathrm{DOC_{ld}}$) flux in runoff was significantly linear correlated with throughfall with the highest increase rate of $\mathrm{DOC_{ld}}$ in pure *C. lanceolata* stand ($y = 0.934x - 1.762$; $P < 0.001$; $R^2 = 0.727$). On the basis of these results, pure *C. lanceolata* stand may lead to more deterioration of soil productivity in the investigated area. For the sustainability of the soil productivity, forest management should make some changes to reduce the area of pure *C. lanceolata* stands in the laterite hilly region of southern China. The mixed *C. lanceolata* stands with *P. elliottii* or broadleaved forests, such as *S. superba* and *C. jenseniana*, are recommended for the reforestation in this region with further investigation.

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